Assessment of Mars Phoenix EDL Performance

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Abstract—Entry, Descent, and Landing (EDL) is an especially risky phase of a planetary mission, and detailed information on the performance of a lander's EDL design is critical to mitigating the risks of future missions. 12However, the study of actual EDL performance and comparison with the pre-entry predictions has not typically been given a high priority following spacecraft landings, mainly for budgetary reasons. Because Mars Phoenix inherited hardware and design elements from a similar mission that appears to have failed during Mars EDL, NASA was particularly interested in identifying the reasons for the Phoenix mission success. Therefore, NASA sponsored a reconstruction and analysis of the downlinked Phoenix telemetry that would tell the story of this critical event sequence—focusing on the 14 minutes from cruise stage separation to landing—and identify lessons learned.

Phoenix EDL was very successful—a harbinger of a Mars polar surface mission that exceeded its objectives:

- *Cruise Stage Separation* was nominal, with no indication of lander recontact with the cruise stage.
- During *Hypersonic Entry*, the lander trimmed at a higher angle of attack than predicted. The decision to widen the Reaction Control System (RCS) deadbands to prevent control reversal was justified by the results.
- *Parachute Deployment* was nominal, except for some delay due to the higher angle of attack.
- *Heatshield Separation* was nominal, with no indication of recontact with the lander.
- The *Terminal Descent* trajectory closely matched the pre-entry prediction, with no terminal descent or radar performance surprises.

The study also addressed several questions that arose following the landing (e.g., "Why did Phoenix land long?" and "Was there a plasma blackout?").

NASA plans to use the study results to improve future Mars EDL models and prediction tools and to optimize future system and mission designs that feature an EDL phase. The results of the Phoenix EDL reconstruction appear useful enough to justify including such a task as a normal post-landing activity, and for NASA to allocate funds for it within the flight project budget.

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1. INTRODUCTION

Entry, Descent, and Landing (EDL) may be the most risky phase of a planetary mission, and spaceflight projects give it commensurate priority in mission design. The spacecraft's great distance from Earth during the EDL phase typically mandates a mostly automated process, despite incomplete knowledge of spacecraft performance and of the varying

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conditions to be encountered. The critical EDL sequences take place over a period of only a few hours, with limited opportunity for error correction. Achieving a landing on Mars is particularly challenging due to constraints posed by descent through a partial atmosphere that are not encountered in either a vacuum or at Earth atmospheric pressure. (For example, because the Mars atmosphere in thinner than Earth's, deceleration occurs at a lower altitude, leaving less time to conduct subsequent EDL events.) Only 5 of 11 attempts by spacefaring nations to land on Mars have been successful. Consequently, information on the actual performance of a given Mars EDL design is of great interest to engineers and mission planners.

Detailed information on EDL performance has not been readily available from Mars landers. Some spacecraft flight systems have not included a dedicated transmitter capable of downlinking telemetry during EDL. On spaceflight projects where EDL data is obtained, there may be no project funding provided for data reconstruction and analysis because the direct benefits from the study would be accrued mainly by future projects. Therefore, post-landing EDL performance study has not been an established activity in project implementation plans.

In May 2008, the NASA/Caltech Jet Propulsion Laboratory (JPL) achieved the first successful landing in a Martian polar region with the Mars Phoenix lander. Phoenix was the successor to a 1999 attempt at a polar landing by Mars Polar Lander, which reached Mars, but is not believed to have survived EDL. Because this 1999 mission loss called NASA technical capabilities into question, a Mars Surveyor 2001 Lander project was cancelled in 2000. Although Phoenix inherited components and design elements from both these previous projects, JPL used the 6-year delay to make significant improvements to EDL technology and other elements of the Mars lander flight system design that may have led to the Phoenix mission success.

2. METHODOLOGY

Following the successful 2008 landing of Mars Phoenix, the NASA Office of the Chief Engineer and the NASA Aeronautics Research Mission Directorate commissioned a reconstruction of the EDL data telemetry [1]. By improving NASA's understanding of Phoenix flight performance (i.e., comparing the actual flight performance against the pre-entry predictions of flight dynamics, aerodynamics, and aerothermodynamics), the sponsors sought to improve the accuracy of the prediction tools and environmental models and address some questions that arose following Phoenix EDL. The downlinked data available to the analysts included channelized engineering telemetry; non-channelized gyro, accelerometer, and radar data; navigation data on the spacecraft entry state; the landing location coordinates; and radiometric data on EDL communications.

Channelized engineering telemetry typically consists of data which has been processed and time-tagged by the on-board computer and is intended to be used to monitor spacecraft health and safety. Examples include hardware power states and software mode states, angular velocity estimates in spacecraft body coordinates, spacecraft attitude, etc. Channelized telemetry requires significant computational resources to package and time-tag the data and significant bandwidth for transmission, so the sample frequency of channelized telemetry is usually limited to the flight software real-time interrupt (RTI) frequency (10 Hz, for Phoenix).

Unlike channelized telemetry, non-channelized telemetry usually consists of data which is either generated at a much higher sample rate than the flight software RTI frequency or is simply too large or unwieldy to "fit" into a conventional engineering telemetry channel and which generally undergoes little or no processing by the onboard computer. It is essentially raw data. Examples of non-channelized telemetry for Phoenix include IMU data sampled at 200 Hz (angular change measurements from each of three gyroscopes and linear velocity changes from each of three accelerometers) as well as landing radar Doppler spectra sampled at 10 Hz. Another important difference between channelized and non-channelized engineering telemetry is that channelized telemetry is typically collected throughout the mission, albeit at very low sample frequencies in some cases. Non-channelized telemetry, however, is usually only collected during special events (e.g., EDL) when extra visibility into vehicle performance is required.

Because non-channelized telemetry is raw, ground processing is usually required. For Phoenix, the 200 Hz IMU data collected during EDL was used to forward-propagate the vehicle state (position, velocity, attitude, and attitude rate) from entry to touchdown. The same IMU data was also used to reverse-propagate the vehicle state from the landing site to entry. The two trajectories, while not identical, matched to within a few hundred meters in position through the trajectories—an excellent match.

The non-channelized landing radar data was used in several ways. First, pictures of the Doppler spectra were generated to subjectively assess the quality of the data. The key measurement generated by the spectra is a frequency spike indicating the Doppler shift from which velocity in the radar beam direction can be extracted. If this spike is not unique or easily identifiable, then the onboard radar processing software may select the wrong peak and thus introduce a velocity measurement error. Next, the Doppler spectra were compared against equivalent spectra generated by a high-fidelity computer model of the radar that was "flown" using the actual Phoenix trajectory. The purpose of this exercise was primarily to validate the computer model: the results matched.

Phoenix radiometric data from communications during EDL did not have a significant role in the analysis.

3. KEY FINDINGS & RECOMMENDATIONS

Although EDL is typically the highest risk phase of Mars surface missions managed by JPL, Phoenix EDL was very successful. After a landing that was flawless in respect to achieving mission objectives, Phoenix returned a wealth of information on the geologic history and biological potential of the Martian arctic, and remained active on Mars for months longer than the planned lifespan. From an EDL design perspective, however, there were a number of lessons to be learned from Phoenix performance during this critical period in the mission. Based on the data reconstruction [1], the vehicle performance during the EDL sub-phases (Figure 1) may be characterized as follows:

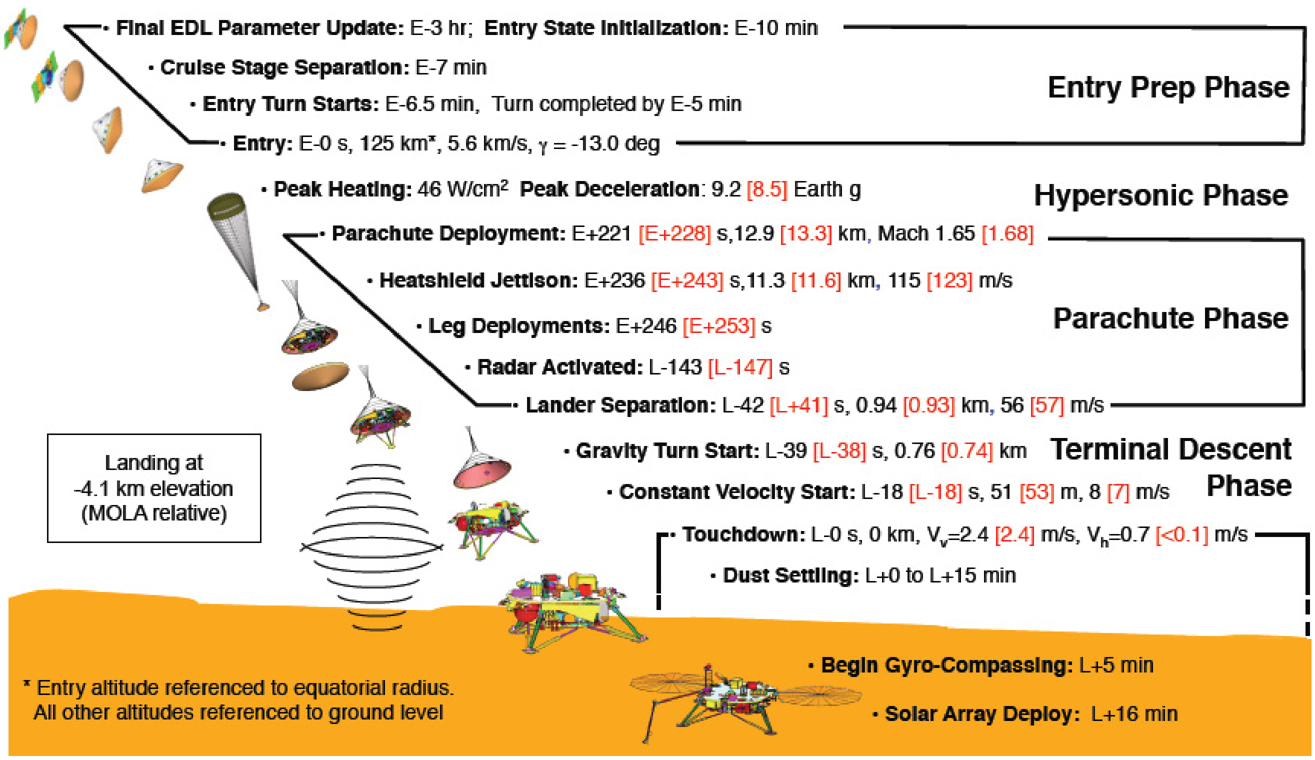

Figure 1 – Nominal (actual) Phoenix EDL sequence

(1) *Cruise Stage Separation*—The spacecraft state was nominal up to cruise stage separation, and the vehicle performed well upon atmospheric entry. There was no indication of lander recontact after separation from the cruise stage.

(2) *Hypersonic Phase*—During hypersonic entry, it was observed that Phoenix trimmed at a higher total angle of attack than simulation had predicted. Consequently, the vehicle flew a slightly lifting trajectory. Second, since the vehicle was aerodynamically stable, a decision had been made to widen the RCS deadbands throughout the hypersonic regime to mitigate a concern about thrust reversal in this regime. As no thruster activity was recorded during the period from HYPER2 transition through parachute deployment, there was no chance of Phoenix thrust reversal. Third, the vehicle experienced large aerodynamic torques during the deceleration pulse that exceeded the available Z-axis thruster torque, further vindicating the decision to widen the RCS deadbands.

(3) *Parachute Deployment & Descent*—Parachute deployment and inflation met the design requirements. The parachute deployed 6.4 seconds later than predicted, but this is consistent with the indications of a lifting trajectory. Also, the times for line stretch and first-peak-load-from-mortar-fire were slightly shorter than predicted (but within expected variations), and the estimated parachute peak load was well below the flight load requirement.

(4) *Heat Shield Jettison*—Quite unexpectedly, the Phoenix heat shield separation event was seen in an image (Figure 2) captured from the HiRISE camera aboard the orbiting Mars Reconnaissance Orbiter (MRO) spacecraft. The heat shield can actually be observed falling away, 47 seconds after parachute deployment and about 9.2 km above the Martian surface. Based on the HiRISE pixel and image angle, the heat shield was estimated to be about 340 meters below the lander. This may be compared to a pre-entry heat shield separation analysis that predicted a mean separation distance of 395 meters with a 1σ dispersion of 66 meters. Hence, the model-based mean prediction may have been quite accurate as it was less than 1σ

from the image-based estimate. There was no indication of a major heat shield recontact incident during separation.

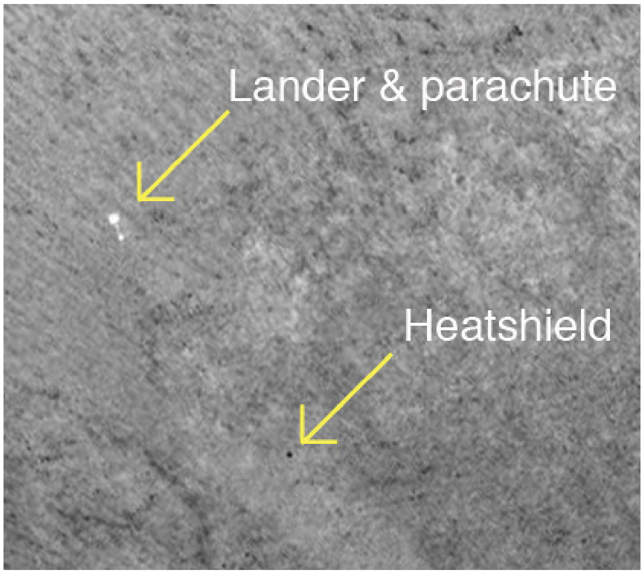

Figure 2 – Phoenix descent observation by the MRO HIRISE camera orbiting Mars

(5) *Terminal Descent*—Overall, the actual descent trajectory matched the prediction quite closely. No anomalies were encountered during terminal descent, with the radar performance nominal and all touchdown requirements met:

- The lander separation from the backshell was nominal, as was the "tip up" rotation used to clear the backshell and align to the gravity-turn attitude.
- A Backshell Avoidance Maneuver (BAM) was implemented to prevent the backshell and parachute from landing on the Phoenix lander. Because of the horizontal velocity at the time of separation, the BAM was not necessary, nor was it executed by the flight software.
- The gravity turn and constant velocity were nominal.
- The touchdown deceleration was within 50 percent of the maximum allowable, the final landing pose tilt/azimuth errors were well within requirements, and the touchdown dynamics met expectations.
- All three touchdown sensors tripped after the lander legs deployed, and the full leg compression needed to register touchdown lasted almost 3 times longer than required.
- The back pressure caused by ground effects (which results in a small upward acceleration of the lander just before touchdown) was observed to begin slightly closer to ground than shown in simulations. But because the onset was slightly faster, the total deceleration was effectively as predicted.

Several questions arose following the Phoenix landing that were subsequently addressed by the study [1]:

(1) *Why did Phoenix land long?*—Due to cancellation of the sixth trajectory correction maneuver (TCM-6) during the Cruise phase, the predicted landing location was updated and re-centered 17 km uptrack of the original target landing location (Figure 3). However, the vehicle landed 21 km downtrack and 5 km crosstrack from the newly predicted site, or a straight-line distance of 21.6 km. The primary cause was the higher-than-predicted angle of attack during hypersonic entry. When this error is combined with the reconstructed atmospheric density and high-altitude winds, and with the very small navigation entry state error (i.e., error in knowledge of position, velocity or entry time) the propagated landing site is within 2 km of the newly predicted landing site (and well below the 1σ uncertainty).

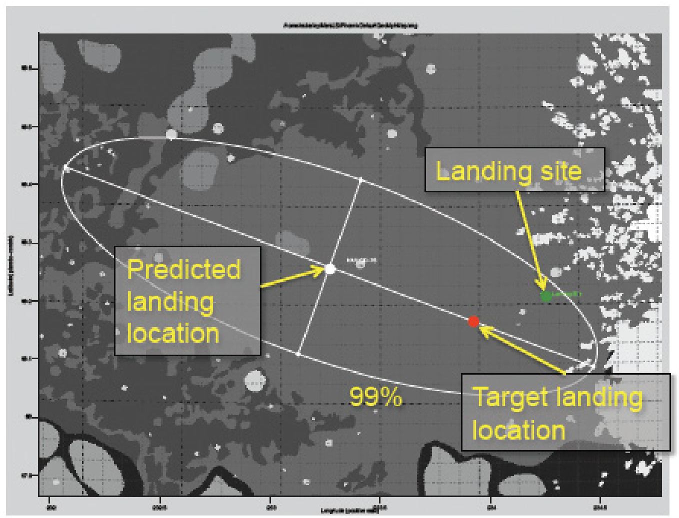

Figure 3 – Phoenix landing ellipse showing actual landing site (green dot) 21.6 km downtrack of the updated predict (white dot)

(2) *Why did Phoenix have an unexpectedly high angle of attack during Hypersonic?*—A difference in the angle of attack prediction will result in different aerodynamic forces and torques than predicted. The effects of this difference are particularly significant during the hypersonic entry, when there is still a long time to landing. A number of candidate causes of the high angle of attack have been identified [2]. However, the likely cause is a combination of a larger-than-expected radial offset in the capsule center-of-gravity location than pre-entry measurements, and a slight overestimate of the capsule hypersonic aerodynamic stability. But there is insufficient data for the EDL reconstruction to conclusively identify the cause.

(3) *Why did Phoenix roll during Hypersonic?*—Phoenix experienced a roll torque of 0.5 Nm at peak

deceleration. This induced a 0.7 deg/sec roll rate that continued through parachute deployment. Roll rate reconstruction showed that bounded aerodynamic instability and a center-of-mass radial offset could produce the observed roll rate. But the EDL data reconstruction did not conclusively determine the cause of the roll.

(4) *Were there any indications of the thruster efficacy issue?*—Thruster jet interactions with the structure (Figure 4) during EDL can alter the pressure on the backshell, resulting in different control moments than intended. RCS pitch authority may be degraded and yaw authority may be low to non-existent, posing a risk of control reversal. Furthermore, this may cause a large attitude error at parachute deployment that leads to excessive wrist mode dynamics that subsequently degrade radar performance. However, since Phoenix did not fire thrusters during the descent, relying instead on the inherent capsule stability to traverse the flight regimes, thruster efficacy was not an issue.

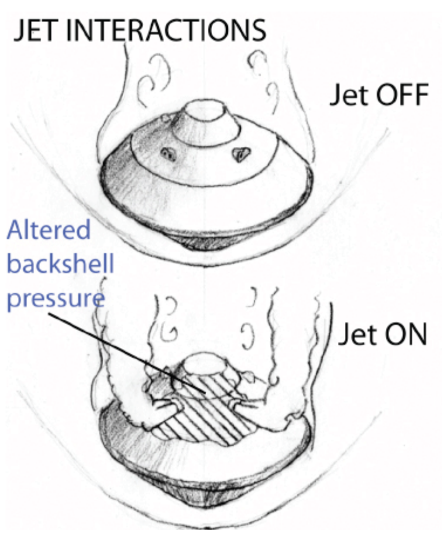

Figure 4 –EDL thruster efficacy issue

(5) *How did the radar perform?*—The Phoenix radar design was inherited from the Mars Polar Lander and Mars '03 projects. Modifications for the Phoenix mission included a lower minimum altitude, high-resolution Doppler mode, new antenna design and configuration, new antenna switch design, lower pulse repetition frequency (PRF) for range ambiguity protection, and numerous firmware updates. The Phoenix radar worked well in the environment for which it was tuned (flat terrain, near vertical descent), and the overall altitude and velocity performance was consistent with simulations and with field testing at NASA Dryden Flight Research Center. One unexplained (but not unexpected) anomaly was seen in the altitude data just prior to touchdown, but well after the system ceased using radar data to control the landing. (Some of the radar performance data discussed in [1] has been omitted here to ensure conformance with International Traffic in Arms Regulations (ITAR) restrictions.)

(6) *Was there a plasma blackout?*—Communications may be attenuated or interrupted when a spacecraft enters an atmosphere due to the ionized sheath of plasma and high electron density caused by the compression and heating of surrounding air. Phoenix was equipped with a transmitter capable of both recorded and real-time downlink via both Mars orbiter relays and direct-to-Earth. EDL downlink was maintained from 2 minutes prior to Entry until 1 minute after touchdown. Phoenix telemetry suggests that there may have been a short communications brownout or blackout during the period of peak heating during planetary entry.

(7) *Was there any fault protection activity or anomalies during EDL?*—All high-level and component-level fault protection counts during EDL were either expected or understood. These included 315 X-axis attitude control error counts during parachute descent (expected), 531 radar reliable counts (expected), 1 Fast Fourier Transform (FFT) Frozen count (understood) and 1 FFT Done count (understood). There were no other EDL anomalies.

4. PLANS FOR FUTURE WORK

JPL and NASA plan to utilize the findings of the Phoenix EDL reconstruction for the improvement of future Mars EDL models and prediction tools, and for optimizing future system and mission designs that feature an EDL mission phase. For example, the analyzed Phoenix EDL data will allow NASA to fine tune its Aero Database that is used to determine forces and moment for Viking-analogue symmetric sphere/cone hypersonic entry vehicles given such parameters as angle of attack. Lack of fidelity in this database model of the aerodynamics for the transition between the free molecular and continuum fluid regimes degraded the prediction of the Phoenix EDL trajectory and increased the landing site error, as evidenced by unexpected external torques measured by the MIMU. The mismatch between the model and the flight data is being investigated to improve model fidelity.

Another application of the Phoenix EDL data was validation of the high-fidelity radar model developed for Phoenix. JPL compared the raw radar data from the Phoenix landing with the predicted radar measurements and found them to be consistent, the only discernable difference being a slightly weaker return seen in the radar telemetry from the Phoenix EDL data that had no appreciable effect on the performance of the radar altimeter/velocimeter. Had they not matched, the radar model would have been modified to improve its performance for future missions.

Decreased uncertainty in Mars EDL predictions will result in greater confidence in future spacecraft EDL designs. This may allow NASA to entertain Mars mission concepts that would otherwise be viewed as too risky.

5. CONCLUSIONS

The Mars Phoenix EDL reconstruction study provided a detailed characterization of the performance of the EDL portion of the mission design and resolved most of the questions still outstanding after the successful landing on Mars. The EDL design met the mission needs and there were no EDL “show-stoppers” that threatened mission success. The major risks that are encountered in planetary EDL, such as lander recontact with the cruise stage or heat shield, inaccurate determination of altitude, thruster efficacy and thrust reversal, anomalous parachute deployment, anomalous descent trajectory, anomalous touchdown sensing, and post-landing parachute/backshell recontact with the lander, were successfully mitigated by the Phoenix project. This may be attributable to a robust system design for EDL, the extensive Phoenix test program, the choice of a ballistic entry instead of hypersonic guidance, a manageable EDL timeline due to a benign entry velocity and low landing site elevation, and the addition of a Backshell Avoidance Maneuver [3].

Following a successful planetary landing, the balance of project and mission resources is typically devoted principally to assuring successful surface operations. However, unless an analysis of system performance during the critical EDL mission phase is undertaken, it may be difficult later to reconstruct EDL performance data that may be critical to the success of future missions. NASA should consider allocating resources in flight project budgets for an EDL reconstruction to be scheduled as soon after planetary landing as feasible.

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BIOGRAPHY

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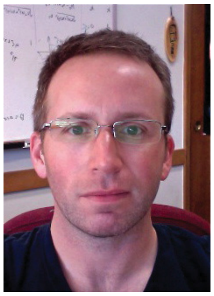

Eli David Skulsky is a Senior Engineer in the EDL Guidance and Control Systems Group at JPL. He has been at JPL since 1993 and has been a member of the G&C teams for a number of missions, including Mars Observer, Cassini, Mars Reconnaissance Orbiter, and the Mars Phoenix Lander, for which he served as the Deputy Entry, Descent, and Landing Lead. David is presently the G&C and Lunar Descent and Landing Lead for the proposed MoonRise New Frontiers mission.

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